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CONTROLLED THERMONUCLEAR REACTIONS FOR SPACE PROPULSION

ROBERT F. COOPER
RICHARD L. VERGA

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NOTICES

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FOREWORD

Each year the Aeronautical Systems Division (ASD), Air Force Systems Command (AFSC), sponsors a Science and Engineering Symposium in advance of the Annual Air Force Science and Engineering Symposium. This provides a specific motivation for ASD personnel to prepare papers that reflect the results of their efforts. The variety of subjects also provides an opportunity for interdisciplinary exchange of information that is becoming ever more important.

This year the symposium papers are being published individually to facilitate distribution and retention. However, each paper carries this same foreword which lists the titles of all papers together with the authors and the ASD Technical Documentary Report (TDR) numbers. Readers who are interested in obtaining copies of other papers are urged to contact the authors directly or the Defense Documentation Center, Alexandria, Virginia. It should be noted that certain papers are classified and are available to only those persons having proper security clearances and a "need-to-know."

This paper is one of 21 presented at the "ASD 1963 Science and Engineering Symposium" held at Wright-Patterson Air Force Base, Ohio, 18-19 September 1963. They consist of 17 CONTRIBUTED and 4 INVITED papers, listed below. *The 5 contributed papers that are asterisked were also presented at the 10th Annual Air Force Science and Engineering Symposium held at the Air Force Academy, Colorado Springs, Colorado on 8, 9 and 10 October 1963.

CONTRIBUTED PAPERS

*Operation Fishbowl — Close-In Thermal Measurements, UNCLASSIFIED Title, SECRET-RESTRICTED DATA Paper
F. D. Adams
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Radiation Physics: Its Impact on Instrumentation
R. C. Beavin, 1st Lt, USAF
ASD-TDR-63-697

*Application of Aerodynamic Lift in Accomplishing Orbital Plane Change
R. N. Bell, 1st Lt, USAF and W. L. Hankey, Jr., Ph. D.
ASD-TDR-63-693

Controlled Thermonuclear Reactions for Space Propulsion
R. F. Cooper and R. L. Verga
ASD-TDR-63-696

Comparison of Approaches for Sonic Fatigue Prevention
M. J. Cote
ASD-TDR-63-704

Air/Ground Communications Via Orbiting Reflectors
C. C. Gauder
ASD-TDR-63-702

*Ring Laser Techniques for Angular Rotation Sensing
D. A. Guidice and W. L. Harmon
ASD-TDR-63-694

Zero Gravity Pool Boiling
L. M. Hedgepeth and E. A. Zara
ASD-TDR-63-706

An Analytical Study on Liquid Cesium Purification in View of Current and Projected Needs
R. H. Herald
ASD-TDR-63-703

*Preliminary Weight Estimates for Advanced Dynamic Energy Conversion Systems
G. D. Huffman
ASD-TDR-63-705

Force Balance Determination of Inlet Performance for Advanced Vehicle Applications to Orbital Velocities Using Internal Drag Measurements
P. H. Kutschenreuter, Jr.
ASD-TDR-63-701

Thermal Insulations for Aerospace Applications: -423° to + 3000°F
M. L. Minges, 1st Lt, USAF
ASD-TDR-63-699

The Rankine Cycle Air Turboaccelerator (RATA) Engine — A New Cryogenic Engine system, UNCLASSIFIED Title, CONFIDENTIAL Paper
H. E. Pope
ASD-TDR-63-692

How PERT is Used in Managing the X-20 (Dyna-Soar) Program
R. M. Sadow
ASD-TDR-63-698

Liquid Metal Magnetohydrodynamic Power Conversion
G. B. Stafford
ASD-TDR-63-700

System Components Information Center
M. G. Toll
ASD-TDR-63-695

*Aerospaceplane — An Advanced System Planning Study, UNCLASSIFIED Title, SECRET Paper
Alan Watton
ASD-TDR-63-690

The following four invited papers were prepared by the listed authors covering Air Force effort in the subject areas and were presented at the 10th Annual Air Force Science and Engineering Symposium. Copies of these papers may also be obtained from the authors or the Defense Documentation Center.

INVITED PAPERS

A large percentage of the above listed authors are with organizational elements that have been or are being transferred from ASD to the recently established Research and Technology Division (RTD). These scientists and engineers from the Air Force Aero-Propulsion Laboratory, Air Force Avionics Laboratory, Air Force Flight Dynamics Laboratory, Air Force Materials Laboratory, and the Systems Engineering Group have, in some cases, prepared the symposium presentations as well as the published documents jointly with technical personnel remaining in ASD.

These 21 papers represent only a small portion of the ASD/RTD effort which spans from basic research through engineering and includes various aspects of technical management. They are illustrative of the competence of our technical personnel and we proudly dedicate them to all our scientists and engineers.

John E. Keto

JOHN E. KETO
Chief Scientist
Aeronautical Systems Division

BIOGRAPHIES

ROBERT F. COOPER was born at Muskegon, Michigan and educated at Michigan College of Mining and Technology and the Air Force Institute of Technology, receiving a Master of Science degree in nuclear engineering from the latter institution in 1959. He is currently working towards a Ph. D. degree in physics through the Ohio State University Graduate Extension Program. Since graduation, he has been assigned to the Propulsion Physics Branch of the AF Aero Propulsion Laboratory, Wright-Patterson Air Force Base (WPAFB), Ohio. Currently, he is serving as a Group Leader in research for the evaluation of new, nonchemical, advanced concepts for propulsion. Mr. Cooper has coauthored a number of technical documentary reports dealing with advanced nuclear propulsion concepts. Mr. Cooper is a member of the American Nuclear Society, the American Institute of Aeronautics and Astronautics, and Phi Lambda Upsilon.

RICHARD L. VERGA was born in Milwaukee, Wisconsin. He received a B. S. degree in physics from the Illinois Institute of Technology, and has presently completed a majority of the course work required for the M. S. degree in physics from Ohio State University. Since 1960 Mr. Verga has been associated with the Propulsion Physics Branch of the AF Aero Propulsion Laboratory. His duties have consisted primarily of the analysis and evaluation of advanced nonchemical propulsion concepts. He has coauthored a number of technical documentary reports dealing with advanced nuclear propulsion concepts. Mr. Verga is a member of the American Institute of Aeronautics and Astronautics.

ABSTRACT

A propulsion system utilizing controlled thermonuclear reactions as an energy source is shown to possess definite advantages over all other propulsion systems in the performance of those space missions requiring a high velocity increment. No valid argument exists which indicates that controlled fusion will not be achieved. In addition, analyses indicate that no insoluble engineering problems would be associated with the adaption of controlled fusion to the propulsion of a space vehicle. A number of applicable areas of technology are discussed. These areas are either being pursued at the present time or require additional intensive effort. The inherent potential of the application is such that pursuit of this energy source for propulsion cannot be ignored nor delayed.

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ILLUSTRATIONS

INTRODUCTION

In the evolution of air power into space power, the leadership of the U.S. has been seriously challenged in an area in which this country was for years without real competition-technology. The rate at which we advance is no longer of our own choosing. Rather, this rate is paced to meet the demands of a very serious competition - a competition in which the security of our nation is at stake.

In order to achieve and maintain the lead in space, we must constantly watch for, explore, and exploit new techniques to give us the needed technological quantum jumps forward. We must, for example, ever be on the alert for new and radical methods to surmount present propulsion limitations. A major step in this direction would be the successful development of thrustors using thermonuclear reactions as energy sources.

MOTIVATION

NUCLEAR POTENTIAL

The advent of the new technological age in which we now find ourselves has emphasized with startling clarity the most important single weakness in our technical posture - the lack of adequate power. This weakness has inhibited engineering progress throughout modern history and is stifling the realization of many of our technological goals today. The history of the technology of this century is fraught with examples of the attainment of goals being thwarted by the lack of necessary power in a sufficiently small and lightweight package. Whether this power is needed for prime propulsion or for the most insignificant of auxiliary systems, it is not only the absolute magnitude of the power which is important; rather it is the degree to which this power is usable. The power required to perform a particular task must be compressed into a package small enough, light enough, and which possesses sufficient lifetime to make possible the increased capability required for the exploration of the new technological frontiers.

Recent developments in the space programs of this country reemphasize the need for powerful, lightweight, long-lived power supplies for propulsion. Present day large chemical rockets, while performing admirably the task for which they have been designed, are totally inadequate for fulfilling advanced high energy space mission requirements. This fact is well recognized within the propulsion community. Also recognized is the obvious solution to the dilemma - the utilization of nuclear energy sources. Only through the use of nuclear, rather than chemical, energy sources may the power requirements of future generation space vehicles be met (Fig. 1). In this chart the conversion of mass to energy is based on "photon" processes with the total annihilation of matter as unity. In chemical systems, the energy available in combustion provides the major limitation.

The choice of the method by which the tremendous potential of nuclear energy may most readily and effectively be utilized is of primary importance. The nuclear fission heat transfer rocket, a concept now being accorded increasing emphasis, is the first hesitant step in this direction. With this system the energy produced in fission is used to heat a propellant which is then released through a nozzle to produce thrust. In this manner specific impulses can be achieved that are more than twice those produced by the most advanced chemical rocket. Although attractive, these specific impulses are still more than an order of magnitude below those required for most space ventures of the future.

TYPE	MASS – ENERGY CONVERSION	CYCLE
CHEMICAL	5×10^{-11}	DIRECT (TURBINE, NOZZLE)
FISSION	10^{-3}	THERMAL
FUSION	4×10^{-3}	DIRECT
PHOTON	1	DIRECT

Figure 1. Propulsion System Limits

An attempt to use the nuclear energy of fission directly as thrust is being pursued in the development of gas core nuclear reactors. Although the concept shows definite merit, it is far from the ultimate in energy utilization even assuming that all the complicated problems associated with a device of this type are solvable.

The alternative approach to the use of nuclear energy that is now being explored on an ever-accelerating basis is the marriage of a nuclear-electric power supply with an electrical accelerator. Recent developments have shown that electrical thrust devices can accelerate propellants in the form of plasma, ions, or colloidal particles to specific impulses ranging from 1000 to 20,000 or even 30,000 seconds. Here, it appears, has been developed the first true space drive, the first engines which, because of their amazingly high fuel utilization efficiency, appear to fulfill the requirements of true space thrustors. Unfortunately, it is here that the basic problem plaguing all technological development is encountered in its most fundamental form. Power, in the form of a long-lived, lightweight electrical supply, is not available. The electric thrustors will require electrical power supplies of, initially, many kilowatts, later many megawatts, eventually many tens or even hundreds of megawatts. Because of its high specific impulse, the propellant required for an electrical thrustor is much less than that required for a chemical rocket to perform the same mission. However, the electrical thrustor together with its required power supply and associated conversion equipment is far too heavy to produce thrust-to-weight ratios which even approach unity. The promising applications for electric propulsion are therefore limited to those regimes for which a thrust-to-weight ratio of 10^{-5} to 10^{-3} is acceptable. It is an inescapable fact that the specific weight (pounds per kilowatt) of the power plant is of primary importance in determining the utility of electrical propulsion.

As presently conceived, nuclear-electric turbogenerators will possess specific weights from as high as 400 lb/kw down to a possible ultimate minimum of 10 lb/kw. With these specific weights, electrical propulsion devices can accomplish a host of missions with definite advantages over chemical systems. However, the panacea for all space flight ills, the versatile true space propulsion device, has not as yet been found.

Are these forms of nuclear energy utilization which have been discussed above the ultimate? Obviously, they cannot be. For in these applications the nuclear energy which

is produced at high kinetic energies (kinetic temperatures equivalent to billions of degrees) is degraded to the level of the temperature of structural materials, several thousand degrees. In the case of an electrical power supply, the thermal cycle production of electricity is, at best, some 8 to 10 percent efficient! One cannot help but conclude that surely there must exist some means by which this inherently distasteful thermal cycle may be eliminated and, in a manner analogous to a chemical rocket, the energy produced by a nuclear power source be manifested directly as thrust.

As the destructive power of the hydrogen bomb dwarfs that of the fission bomb, so the production of usable energy by controlled thermonuclear reactions dwarfs the capability of any fission process. The source of power that is presently the ultimate realizable by man is the nuclear fusion process. In the application of the fusion source to propulsion, it appears that for once the power demands of the future can be adequately programmed and met; the fusion energy source can be utilized in the direct conversion of energy into thrust!

A philosophical question of some magnitude is posed by the seemingly discouraging fact that a sustained controlled thermonuclear plasma has never been achieved. Through some 10 years of concentrated research, however, it has been concluded that there exists no valid reason why controlled thermonuclear reactions should be impossible to achieve. It is interesting to note that limited controlled fusion exists at the present time. Two diversified examples are the sun, which derives its energy from the fusion of hydrogen, and commercially available portable laboratory neutron generators. These latter use the fusion reaction to generate high energy neutrons. At the other end of the scale there is of course the uncontrolled release of energy from thermonuclear weapons. The assumption is justifiably made, in the fusion program of this country as well as those of the rest of the world, that a controlled thermonuclear reaction net power balance will be achieved in the near future.* The question is merely one of timing. In view of the vast reserves of available fissionable materials, the use of fusion energy for the generation of terrestrial electrical power, while a goal of considerable importance, is not considered a problem requiring immediate solution (unless one considers the national prestige of being first!). It is a reasonable contention, however (and it might be added parenthetically that this view is widely accepted throughout the scientific community, including the Soviet Union), that the utilization of controlled thermonuclear reactions for the generation of power for space, whether in the form of electricity or thrust, is critical and is most urgently needed. If the pace which has been established for the conquest of space is to be maintained, if space exploration is ever to progress from the status of laboratory experimentation to that of true feasible space exploration and travel, then the development, utilization, and exploitation of controlled thermonuclear reactions for space is imperative.

Making the obviously correct assumption (identical to that of the world's fusion programs) that controlled fusion will be achieved, it is instructive to consider the implications of this awesome energy source in its application to the production of thrust in space.

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*An interesting fact to note here is that controlled thermonuclear reactors cannot produce a thermonuclear explosion - contrary to fission reactors being able to go "prompt critical" and produce a small fission bomb. The amount of material available in a controlled thermonuclear reactor is orders of magnitude below the "critical mass" required for a nuclear explosion.

FUSION

Two basic problems are encountered in attempting to achieve a controlled thermonuclear reaction; these are the method of heating a gas or plasma to the millions or billions of degrees required, and the means by which the heated plasma may be confined within a suitable volume. If fusion reactions are to produce sufficient power to be self-sustaining, they will occur in a plasma having a temperature and density which is above some minimum value. Once the plasma has been confined in a suitable manner, the coulomb barrier (like-charged particle repulsion) between particles must be surmounted before thermonuclear reactions take place. The particles must be given enormous amounts of energy, equivalent to temperatures of billions of degrees, so that they may approach closely enough to coalesce and undergo a fusion reaction. The coulomb barrier is proportional to the product of the participating ion charges. In view of this, and of the fact that the radiation losses characteristic of a fusion reaction are proportional to the square of the atomic number of the isotopes, only the isotopes of hydrogen and helium may undergo thermonuclear reactions at ion temperatures which may hopefully be obtained.

The thermonuclear reactions which are generally considered to be of interest are:

$$(1)\quad D^2 + D^2 \rightarrow He^3 + n^1 + 3.27 \text{ Mev}$$

$$(2)\quad D^2 + D^2 \rightarrow T^3 + H^1 + 4.03 \text{ Mev}$$

$$(3)\quad D^2 + T^3 \rightarrow He^4 + n^1 + 17.6 \text{ Mev}$$

$$(4)\quad D^2 + He^3 \rightarrow He^4 + H^1 + 18.3 \text{ Mev}$$

In these equations, the heavy isotopes of hydrogen are shown as D for deuterium and T for tritium. The energy term in the above reaction equations is the nuclear energy release which is manifested in the kinetic energy of the reaction products. This nuclear energy is the difference between the binding energies of the two original nuclei and the binding energy of the resultant nucleus (Ref. 1).

A propulsion system of resonable size utilizing ordinary hydrogen (H^1) as fuel would be incapable of maintaining a favorable power balance. Any isotopes which have a mass larger than that of helium-3 or atomic number greater than two cannot be used because of the catastrophic bremsstrahlung losses which occur. The minimum ideal operating temperature (corresponding to the average particle energy) is $\sim$ 36 kev for the D-D reaction, $\sim$ 4 kev for D-T and $\sim$ 80 kev for the D-He^3 reaction, where 1 kev is equivalent to 1.16×10^7 degrees Kelvin. In reactions (1) and (3) above, most of the fusion energy is released in the form of neutrons. These uncharged particles are not retained by the plasma; their energy is immediately lost. By utilizing a reaction in which the energy is released as charged particles, power loss is minimized. This neutron production will be seen to assume major importance in the design of a space-weight controlled fusion device.

The deuterium-helium-3 reaction can be utilized to produce only charged particles. The reaction temperature required to make this system attractive (the temperature required to give Maxwellian distribution cross sections high enough for a feasible device) is of the order of 100 kev. At this energy, however, the D-T and the D-D reactions have

appreciable cross sections. It is impossible to avoid the occurrence of some D-D and D-T reactions in a fully fueled D-He^3 system. At a temperature of 100 kev, a few percent of the fusion energy in a D-He^3 system is given off as neutrons from D-D and D-T reactions. Even this low percentage, however, corresponds to an extremely high neutron flux. Since the D-He^3 reaction produces such a large percentage of its energy in charged particles, however, it is the only reaction suitable for space applications.

OPERATING TEMPERATURE

The optimum operating temperature of a thermonuclear device is determined primarily on the basis of cross sections (Fig. 2), particle density, power density, and structural limitations. However, other considerations may necessitate operation at temperatures which are off-optimum (e.g., a temperature desirable on a cross section basis may lead to an increased occurrence of undesired reactions, as in the above case). In addition, the optimum operating temperature might be so high as to be unrealizable in a practical system.

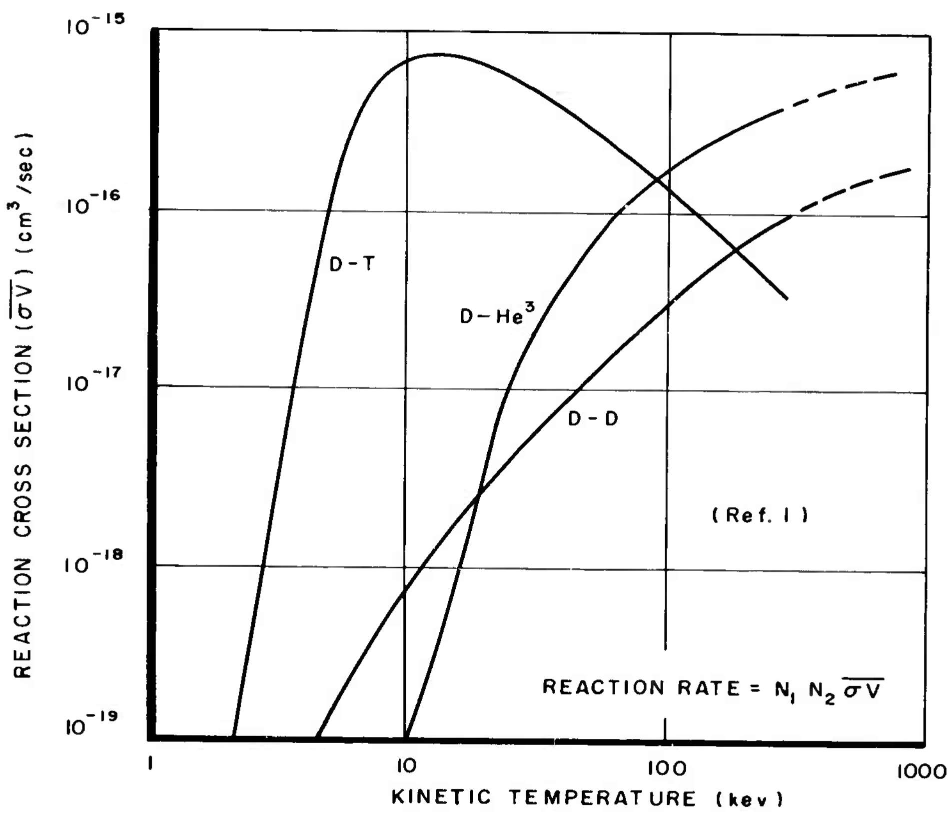

Figure 2. Reaction Rates for Fusion Reactions

CONTAINMENT GEOMETRY

The confinement of a plasma satisfying certain minimum conditions (e.g., suitable energy, density, volume) for a sufficient time presents the major problem in the attainment of controlled thermonuclear reactions. Assuming this confinement, it is generally felt that the other problems associated with the reaction system (production and heating of the plasma, etc.) will be solvable. Because of the extremely high energies involved, it is clearly impossible to utilize a physical containing chamber. Some method of electric or magnetic containment is the logical alternative. Earnshaw's Theorem, together with other qualitative arguments, rules out confinement by electric fields. Consequently, the approach of the Atomic Energy Commission Sherwood Program has been to develop a number of suitable magnetic containers. The most familiar are the pinch, stellarator, mirror, cusp, and variations thereof. In the pinch device, a plasma passing through a conducting tube interacts with its own magnetic field resulting in a compression of the plasma toward the center of the tube. In the stellarator an external magnetic field provides the containment. The mirror coils provide constant central fields with strong end fields, "reflecting" the plasma particles into the central region (Fig. 3). For propulsion applications of thermonuclear processes the magnetic mirror geometry, or some variation, appears the most attractive. In this system, the confining longitudinal magnetic field is applied by means of coaxial current-carrying rings. The field strength is not uniform, but is greater at the ends; a "potential well" is thus formed in the central region, with the mirrors "reflecting" charged particles back into the region of weaker field. Since the mirrors inhibit the escape of the particles in this way, a small difference in the magnitude of the mirror fields will allow leakage through only one of the mirrors. This suggests a simplified approach to the problem of achieving directed thrust.

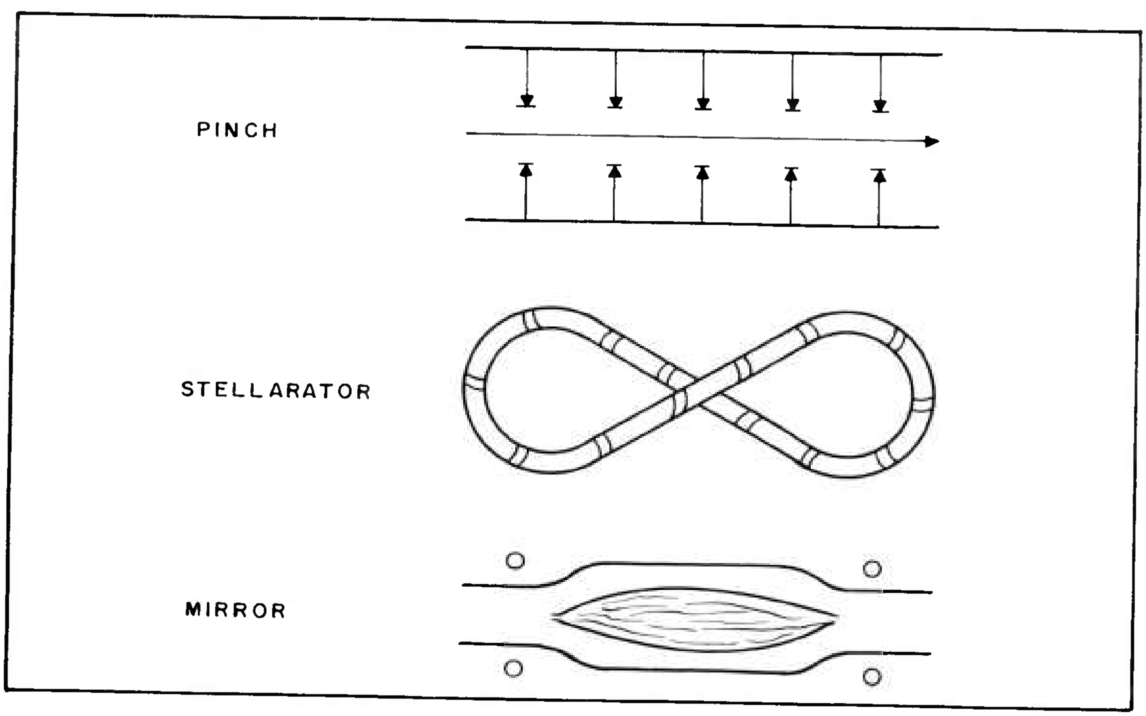

Figure 3. Sherwood Approaches

The major drawbacks of the magnetic bottle are large radiation losses, injection problems, high operating temperatures, and instabilities. It has been suggested that these disadvantages can be partially alleviated by recourse to various "hybrid" configurations. A combination of the basic mirror with the cusp geometry (Fig. 4), as proposed by Ioffe of the USSR, appears promising (Refs. 2, 3, 4, and 5). In this configuration the basic mirror geometry is supplemented by longitudinal current-carrying bars. These bars may be simply straight uncurved conductors, or may be so constructed as to lie along the field lines of the basic mirror.

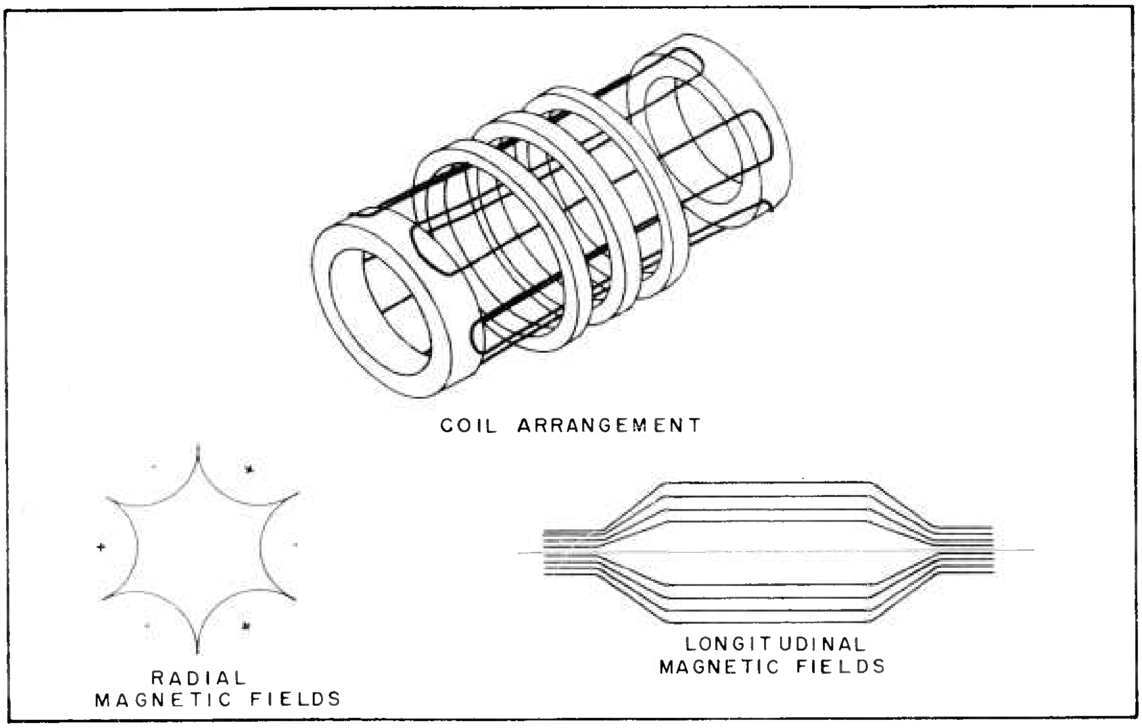

Figure 4. Multipolar Magnetic Confinement Geometry

TECHNICAL BREAKTHROUGH

Prior to the advent of sustained superconductivity in high magnetic fields, those persons who advocated the space utilization of controlled fusion, even assuming the reactors were readily available, were in the class of wanderers in the land of unreality. The magnetic fields associated with the containment of high temperature thermonuclear plasma precluded the attainment of space-weight devices (Refs. 6 and 7). With the discoveries in superconductivity which have occurred since the initial publication of Kunzler in February of 1961 has grown the realization that the technological breakthrough necessary for the adaption of fusion to space use has been achieved (Refs. 8, 9, 10, and 11). While the fabrication of coils of the required dimensions may be difficult, while the solution of refrigeration problems associated with maintaining cryogenic temperatures only inches away from billion degree plasmas requires ingenious engineering design, nevertheless the key for the solution to a heretofore insolvable problem has been obtained.

The generation by conventional electromagnets of the large magnetic fields needed for plasma confinement requires enormous amounts of electrical power and coolant. Magnetic fields of the order of 10^5 gauss, generated by conventional means, require many megawatts of electrical power and cooling. The weight of electrical equipment and cooling system is so large that even if fusion were easily achievable, usable devices for space application would have been completely impractical.

The high power requirements and resistance (Joule) heating can be completely eliminated if the phenomenon of superconductivity is utilized in magnetic field generation. A superconductor has, for all practical purposes, zero resistance below its transition temperature (the critical temperature). Although superconductivity has been known since 1911, its applications have been limited. It was discovered early that the phenomenon was destroyed when the superconductor was placed in a strong magnetic field. The critical magnetic field is that field strength which first destroys superconductivity; the critical field is a function of material. Prior to February 1961, the highest critical fields obtainable were less than a few thousand gauss.

In early 1961, development of superconducting alloys and intermetallic compounds (e.g., Nb_3Sn, V_3Ga, NbZr, and MoTc) made possible the utilization of superconductors in magnetic fields of up to several hundred kilogauss (Ref. 12). The relationship between critical field and critical temperature is shown in Figure 5. It can be seen from this figure that the temperatures of interest are all in the liquid or gaseous helium range. Although it has been shown that a superconductor can produce strong magnetic fields without quenching itself, the attainment of such field strengths in a usable geometry is quite difficult. Nb_3Sn, for example, is extremely brittle; the winding of a large coil of this material has not as yet been accomplished. NbZr is ductile and easily wound into a coil; unfortunately, its critical field is less than 90,000 gauss, and commercially prepared coils generally yield only up to approximately 60,000 gauss. MoTc also has a critical field below 100,000 gauss. A later development, V_3Ga, appears to offer a Bc approaching 500,000 gauss. It too, however, is extremely brittle. The possibility for development of high-field, large volume coils, however, is intriguing. This subject has recently received a great deal of attention (Ref. 13) and developments are proceeding rapidly.

In operation, a perpetual current would be initiated in the coils while the propulsion device is still earthbound. No further power would be required to maintain the current and magnetic field of the coil. The conventional electromagnet cooling system would be replaced by a cryogenic cooling system which will be much lighter in weight, but which will require electrical power for operation.

INJECTION

The "feeding" of fuel into a magnetic mirror is an especially difficult problem since a magnetic field configuration which demonstrates good containment properties for charged particles is automatically a good reflector of such particles. Thus some special means of injecting the fuel into the mirror must be found. Once inside, the particles must be trapped long enough for fusion reactions to occur.

There are two basic approaches to the trapping problem which suggest themselves: (1) high energy injection and (2) "classical" heating (Ref. 14). Various techniques are used to inject charged particles of high energy into magnetic containers for entrapment. The goal is to entrap a sufficient number of particles at high enough energy to ignite a sustained reaction. The so-called classical method of heating consists of ionizing a gas

and then heating it to sufficient temperature (in its container) to ignite a sustained reaction. This heating can be accomplished by magnetic compression, resistive heating, shock compression, etc. The classical heating methods have continuously encountered difficulties with temperature limitations and plasma instabilities. For this reason and because the pulsing of superconducting magnets is impossible, high energy injection appears necessary for space applications of controlled thermonuclear reactions. This approach, previously not emphasized within the Sherwood Program, is presently receiving increased support from the Atomic Energy Commission.

Utilizing high energy injection, it is found that ions of fixed charge-to-mass ratio injected into a conservative field must eventually escape from that field unless acted upon by an external force. A number of suitable approaches (such as molecular ionization) to circumvent or at least delay this effect have been developed within the Sherwood Program. Undoubtedly the most promising approach at present is the magnetic dissociation and injection of energetic neutrals, as proposed by Sweetman of the United Kingdom (Ref. 2). Later efforts by various researchers indicate that the process can be made extremely efficient (Ref. 15).

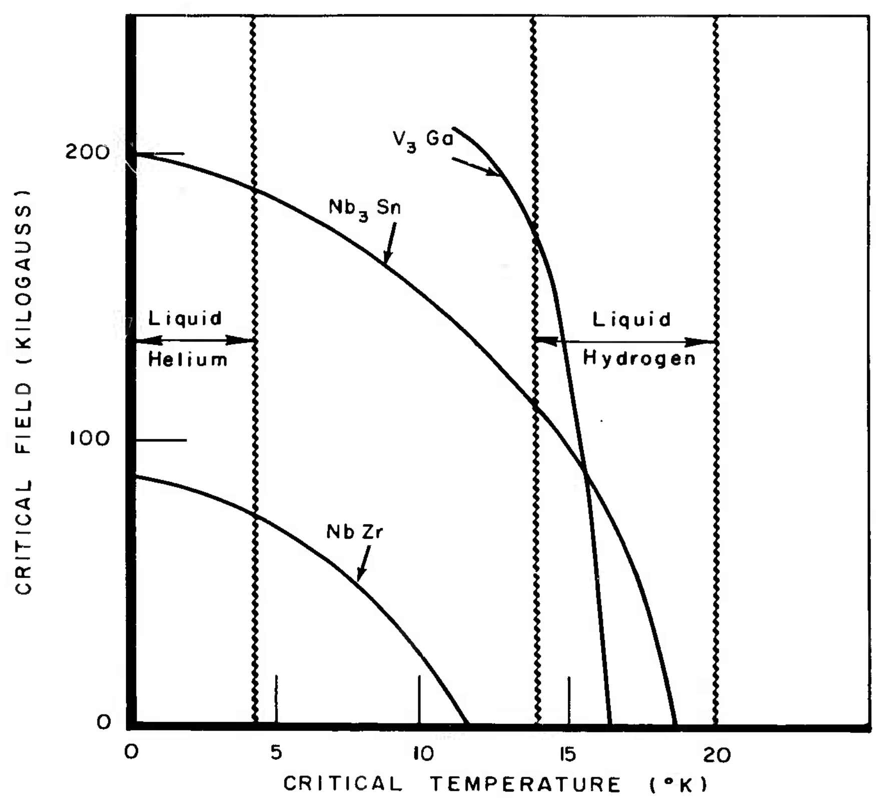

Figure 5. Superconductive Properties

IGNITION TEMPERATURE

The ignition temperature is the minimum operating temperature at which a thermonuclear reaction will become self-sustaining; i.e., the point at which the thermonuclear energy deposited in the system just exceeds the energy dissipated through various loss mechanisms. The major sources of energy radiation from a plasma are bremsstrahlung ("breaking") radiation and cyclotron radiation. Bremsstrahlung, which is radiated in a continuous energy spectrum, arises from the coulomb accelerations of charged particles within the thermonuclear plasma.

Since the power lost through bremsstrahlung is proportional to the square of the atomic number of the plasma ions, and since any impurity in the system will have an atomic number higher than that of the fuel, bremsstrahlung will increase markedly as the impurity concentration increases. The impurity level must therefore be kept extremely low. The temperature at which the thermonuclear energy deposition just exceeds the bremsstrahlung losses is defined as the "ideal" ignition temperature.

Cyclotron radiation is emitted by charged particles undergoing acceleration in spiraling around the flux lines of the externally applied magnetic field. The particles spiral at definite "gyromagnetic" frequencies. The radial acceleration of these gyrating particles is accompanied by the emission of cyclotron radiation. Cyclotron radiation becomes significant when the plasma temperature approaches the ideal ignition temperature.

Bremsstrahlung is emitted in the X-ray and ultraviolet regions of the electromagnetic spectrum, while cyclotron radiation is mainly in the infrared and microwave regions. There is no way of retaining the bremsstrahlung energy in the reactor by reflection or absorption; however, a chamber with highly reflective conducting walls will reflect cyclotron radiation with minimum loss. It is generally felt that if the cyclotron radiation can be passed through the plasma many times by reflection, the energy will be reabsorbed.

In addition to other plasma radiations, thermonuclear reactions release high energy neutrons. These neutrons will not be confined by magnetic fields and their energy will be lost from the plasma. It is of interest to note that a thermonuclear reaction does not release any direct gamma rays.

The actual ignition of a self-sustained thermonuclear reaction occurs when the thermonuclear energy retained in the system just exceeds the energy dissipated by all of the above mentioned processes. A self-contained device, such as a fusion propelled space vehicle, will need to extract additional energy for purposes of injection of fuel and other auxiliary power requirements.

PRODUCTION OF THRUST

The charged particles leaking through the end of a magnetic mirror possess extremely high velocities. Assuming a reasonable reaction temperature, the average particle velocity within the chamber is of the order of 10^5 to 10^6 meters per second. If a Maxwellian distribution of velocities (or energies) is assumed, the highest energy particles will have velocities far in excess of this figure. From scattering considerations, the lower energy particles would be expected to provide the majority leakage from the system. The electrical potentials established because of preferential electron leakage, however, will tend to increase the energy of the escaping particles. On the average, then, the energy of the

escaping particles will be greater than the average particle energy within the chamber. The exahust velocities will correspond to specific impulses (I_{sp}) greater than 10^5 seconds.

These specific impulses will undoubtedly prove to be unnecessarily high for many missions. It would then be possible to increase the thrust of this device and still obtain an I_{sp} which is near-optimum for the particular mission. This optimization or thrust augmentation may be accomplished in several ways.

The most obvious solution to the problem of augmenting the thrust is through the addition of increased amounts of expellant; this expellant would be "heated" by the escaping plasma to some reasonably uniform temperature and would then be exhausted. The criteria upon which optimization is based must be determined and closely analyzed. It is essential that the propellant to be used for augmenting be ionized with minimum loss. This can be best accomplished by operating at those energies which minimize charge exchange and plasma excitation losses. Energy exchange from the high energy, low density reactor beam to the low energy, high density plasma of the augmenter must occur rapidly to minimize size. The augmenter system must be compatible with the fusion reactor. The regulation of mass flow rate or thrust and specific impulse may be achieved by means of the augmenter system. In addition, the generation of auxiliary electrical power by some magnetohydrodynamic (MHD) method decreases the average particle velocity as desired, but unfortunately also decreases thrust.

DESIGN PHILOSOPHY

A schematic of a conceptual fusion propulsion unit is shown in Figure 6. It appears that the major portion of the total weight of an actual controlled fusion propulsion device would consist of structural materials necessary to support the cryogenic coils and auxiliary equipment. The electrical currents which provide the high containment magnetic fields in a mirror geometry will produce attractive forces between the superconducting coils tending to collapse the entire system. The coils must consequently be separated by support structure capable of withstanding compressive loads approaching 10^5 pounds per square inch. In addition, the individual coils will experience radial stresses and must therefore be supported by some hoop structure. There are several materials which appear feasible for these applications. Because of the heat transfer properties of these materials, it may prove necessary to maintain the coil supports as well as the coils at cryogenic temperatures. This should not significantly increase the structural problems since a number of materials possess tensile strengths which, within limits, increase with decreasing temperature. The heat shielding problems will, however, be increased. The primary thermodynamic problems to be considered in the design of a fusion propulsion device are: (1) heating of the superconducting magnetic coils by thermal heat leakage and nuclear radiation; (2) cryogenic refrigeration for removing this heat; (3) recovery of useful power from the waste heat resulting from the attenuation of bremsstrahlung, neutron, and unreflected cyclotron radiation; and (4) rejection of waste heat to space through thermal radiators. These considerations are complicated by the necessity of minimizing weight while maximizing reliability and operational lifetime.

The inner surface of the fusion chamber would be covered with some material which is an extremely good reflector of cyclotron radiation. The chamber would then be surrounded by a bremsstrahlung shield and a neutron shield. Neutron heating of the superconducting coils and of the cryogenic refrigerants will result in a significant heat load.

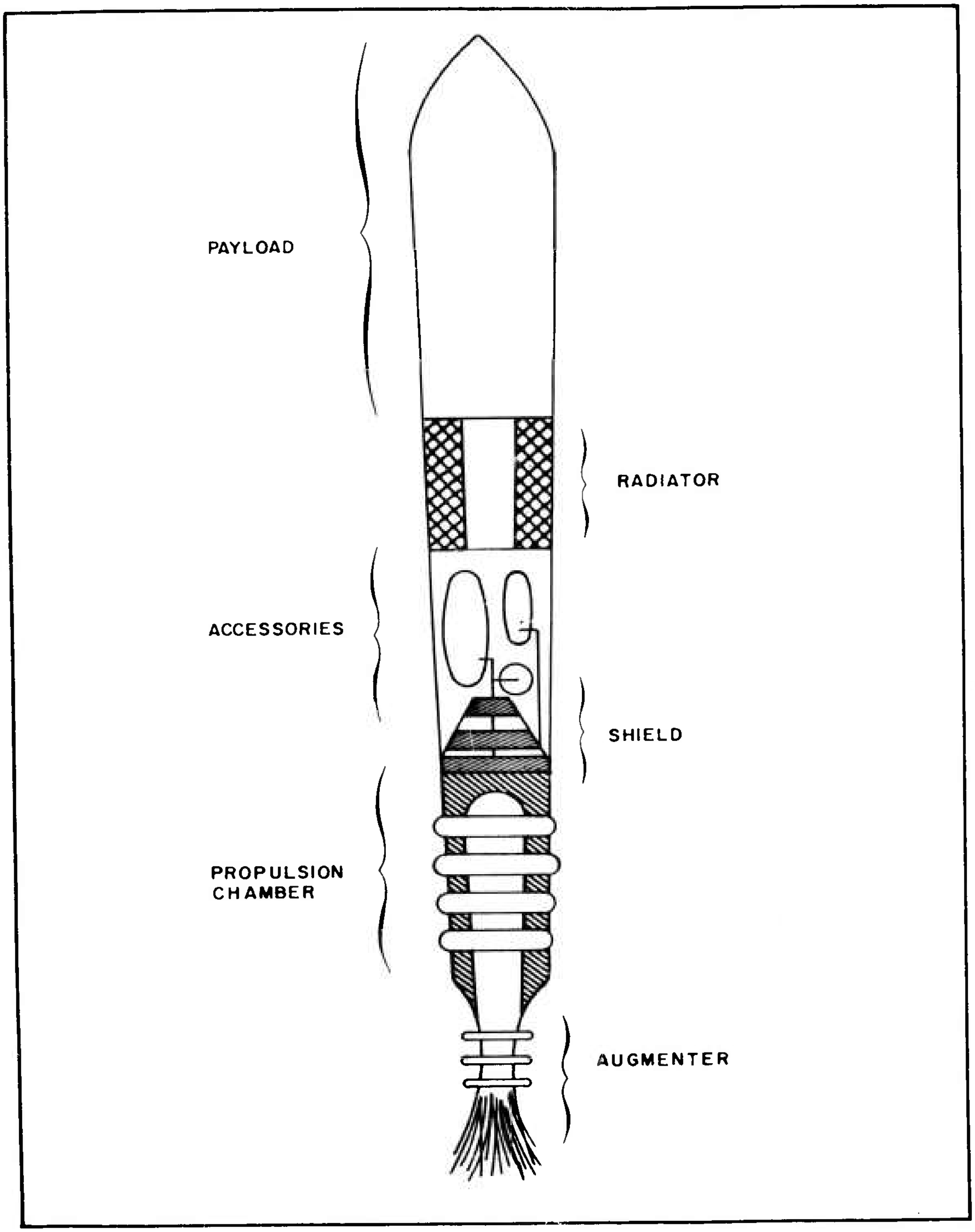

Figure 6. Schematic of a Conceptual Fusion Propulsion System

The necessity of maintaining the magnetic coils at superconducting temperatures ($\sim 5°$ to $10°K$) requires that the coils be well insulated from high temperature heat sources.

The entire vehicle will be subjected to a high neutron flux. If a neutron shield surrounds the reaction chamber, the flux levels will be lowered sufficiently so that structural materials will not be seriously affected. The neutron and secondary gamma loads may still be sufficiently high that large amounts of heat will be deposited in the cryogenics and that the superconducting properties of the coils may be affected. Neutron heating of the coils and support structures will undoubtedly result in a sizable penalty in the form of increased refrigerator weight and power requirements. The shielding which would be required to reduce this flux would also result in a sizable weight penalty.

Neutron irradiation experiments must be performed on all superconductors before they may be considered for fusion devices. In a fusion space propulsion system, space radiation will be negligible when compared with the extremely high flux of 2.45 Mev and 14.1 Mev neutrons from the fusion reactor. High neutron fluxes might destroy the phenomenon of superconductivity; however, it is possible that neutron bombardment may actually enhance superconductivity. Neutron irradiation causes dislocations within the superconductor, and it has been shown experimentally that the critical temperature and magnetic field increase with an increasing number of dislocations.

It is possible to circulate a coolant through the shields, remove some of the heat, and utilize this heat in a thermal cycle for auxiliary power generation. It will undoubtedly prove more advantageous, however, to eliminate the thermal cycle entirely. Utilizing the D-He^3 reaction in which only a small fraction of the total energy is lost through neutrons, this energy might be allowed to escape from the system entirely. The bremsstrahlung shield surrounding the fusion chamber would then be allowed to radiate directly to space.

ADVANCED CONCEPTS

Justification for applied research on a new or advanced propulsion concept must logically follow two criteria. First, the basic research and supporting analytical studies must demonstrate that the propulsion concept is both feasible and potentially competitive with contemporary schemes. Second, the advantages of this concept over those presently available or in the development must be shown. The efficiency of energy production in a fusion reaction is many orders of magnitude above the best chemical process, and a factor of four over a nuclear fission source (Fig. 1) Comparison on the basis of thrust-to-weight ratio, payload fraction, specific impulse, operating lifetime, fuel consumption, and secondary power and auxiliary system requirements show a fusion propelled space vehicle to be definitely superior to other contemporary propulsion devices. The various propulsion systems presently in being or envisaged embrace a wide spectrum of thrust and I_{sp} values. The operating parameters of various propulsion devices are shown in Figure 7. It proves extremely difficult to provide any reasonable common denominator for the comparison of the potential of several propulsion devices in the performance of various missions. For the purposes of illustration, such a comparison might be effected on the general basis of mission energy, which is the total energy increment necessary for mission accomplishment. This rather arbitrary quantity is a function of total vehicle weight and total velocity increment.

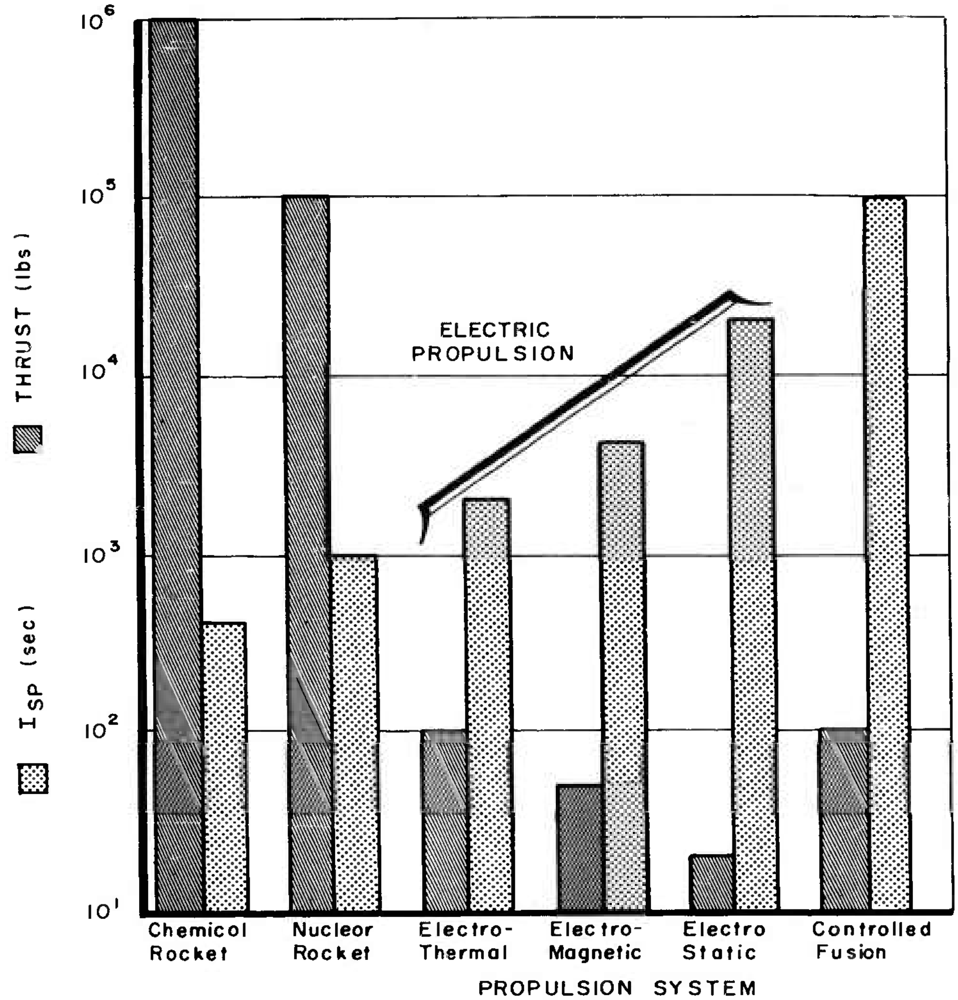

Figure 7. Propulsion Systems Comparison

The equation

$$\frac{\text{Power}}{\text{Weight}} = \frac{g}{2} I_{sp} \frac{\text{Thrust}}{\text{Weight}}$$

is plotted as a function of mission energy in Figure 8. It can be seen from the curves that for low energy missions a large minimum weight propulsion system is severely penalized. With increasing mission energies this disadvantage soon vanishes and the relative system efficiencies become apparent. Only electric and controlled fusion propulsion systems are competitive at very high mission energies (large payloads, long distances). In this regime, the electric systems are limited only by total reactor fuel inventory. The power-to-weight curves are plotted without coordinates. The points of intersection of the various curves will shift with variations in the parameters of individual systems. The curves are merely indicative of general trends.

In space, a thermonuclear propulsion system has the potential of fulfilling the propulsion demands of those missions which require high velocity increments, high payload fractions, large payloads, and moderate reaction and mission times. Studies and calculations of applications of thermonuclear reactions for space propulsion indicate attractiveness, but until the concept is developed such studies can only predict the potential payoff.

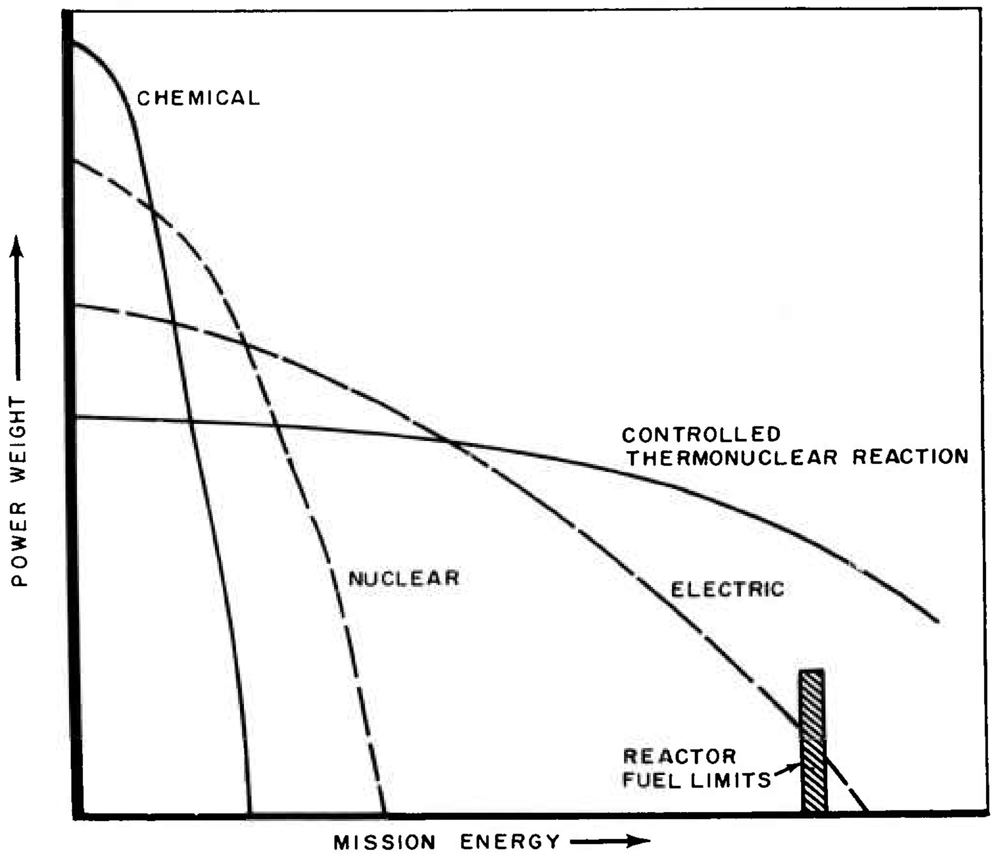

Figure 8. Space Propulsion Mission Capabilities

CONCLUSIONS AND RECOMMENDATIONS

The discussion presented in this paper is intended to serve merely as a simplified introduction to the tremendous potential inherent in the application of the fusion process to propulsion. It is possible to draw, even from this superficial treatment, a number of startling and revealing conclusions.

(1) A controlled fusion propulsion system would possess advantages over all other space propulsion systems in the performance of high-velocity-increment space missions.

(2) The scientific community is convinced that controlled fusion is possible to achieve.

(3) The analyses which have been performed to date indicate that no insoluble engineering problems will be associated with the adaptation of controlled fusion to the propulsion of a space vehicle.

The most suitable approaches of the world's controlled fusion community to the solution of the problems of containment, injection, trapping, burnout, etc., must be examined and analyzed for their applicability to a space propulsion device. It is a well-known fact that when the ultimate goals of particular research programs differ considerably, research guidelines must necessarily differ. An obvious example is the national effort currently under way aimed at the development of ion space thrustors. Research on ion sources had progressed to the point at which highly refined devices could be produced. Upon the generation of a requirement for an ion source suitable for use as a space thrustor, separate detailed and costly development programs were required.

In a like manner, a number of technical areas require immediate intensive effort if the feasibility of the fusion propulsion concept is to be demonstrated in a timely manner. Were a large scale effort in controlled fusion propulsion initiated now, proof of concept feasibility could be accomplished within this decade. Irrecoverable years, so vital in this time of national need, may be lost in the transition from concept to usable device unless the groundwork for this development is laid immediately.

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